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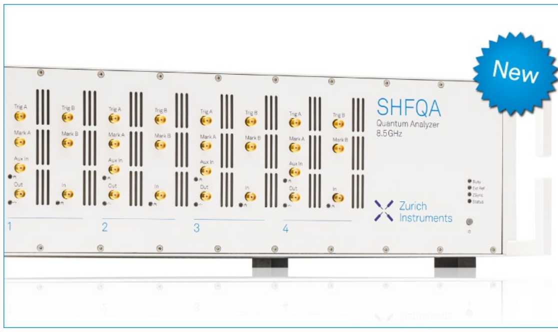

Frequency-Domain Analysis for Pulsating Combustion of Gaseous Fuel

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Abstract. Pulsating combustion is among combustion control methods used to suppress formation of NOx. Past experiments showed that the dependency of NOx content from pulsation rate has a minimum. A measuring unit was set up to study torch behavior in infrared band. To study pulsating combustion of gaseous fuel a thermographic camera was used. Thermographic sequences were recorded using the instrument FLIR 7700M with the resolution of 320×240 pixels at the frame rate of 412 Hz. The experiments resulted in obtaining thermographic sequences radiation intensity fields in the longitudinal section of the torch at different pulsation rates. The obtained raw data was preprocessed to obtain distributions of quantities of pixels corresponding to temperatures in each frame, as well as time-domain series for changes of the torch core longitudinal section area. Frequency-domain analysis was run for each time-domain series using Fast Fourier transform (FFT). The results demonstrate that the first maximum of spectral density coincides with the control action rate. The spectrum also contains pronounced second and third harmonics. For each spectrum of the time-domain series signal-to-noise ratio (SNR) was calculated. Comparison of different SNR shows that maximum impact of pulsation control on torch radiation intensity takes place at the on/off valve opening rate of 4 Hz. This method of torch diagnostics can be helpful for future studies and development of pulsating combustion control systems.
Keywords: Thermal imager, pulsating torch, NOx reduction, Frequency-domain analysis, FFT analysis, Time series.
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INTRODUCTION

Development of combustion processes control system is among the most pressing subjects in modern studies. Not only shall such an automatic control system ensure stability of the combustion process in both steady and transient modes, but it should also provide for measures aimed at achievement of environmentally safe combustion and reduction of noxious substances produced in the process. Reduction of NOx content in residual gas is one of the primary ways to make the process cleaner [1]. There are various ways to control the combustion that directly affecting fuel oxidation and, therefore, NOx content in the residual gas: regenerative injection of air in the burner, forced recirculation of combustion products to the bottom of the furnace or to the burners, steam injection into the combustion zone and so on. In the recent time studies of lean premixed flame combustion are underway [2], including design of special burners for this purpose, such as Low Swirl Burners [3].

Phased combustion is one of commonly used methods employed for NOx reduction. It can be implemented in each burner through arrangement of low frequency pulsations of fuel flow rate while maintaining a constant air inflow rate. In this process, the variable pulsation rate is a control action for the entire In the torch where the burner makes a “striped torch” consisting of sequentially alternating zones with different air content. Further along the gas-air flow path these zones get mixed due to longitudinal heat-mass transfer in the torch accompanied by additional oxidation of the initial products of chemical underburning and the air excess factor in the combustion products reaches the design value.

Past experiments with a direct gas ejection burner demonstrated [4] that the pulsating combustion method helps reduce NOx production. The curve describing the dependency of NOx content from fuel flow pulsation rate had its

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minimum between 4 and 5 Hz at different fuel rates. It is noteworthy that information obtained at one sampling point is insufficient for further development of pulsating combustion and design of control circuit for it. Therefore, it is necessary to develop new flame diagnostics methods that can ensure determination of different flame modes in real time and control the combustion process.

This work discusses frequency-domain analysis of processes in a burning torch subjected to low-rate pulsations of gaseous fuel flow rate.

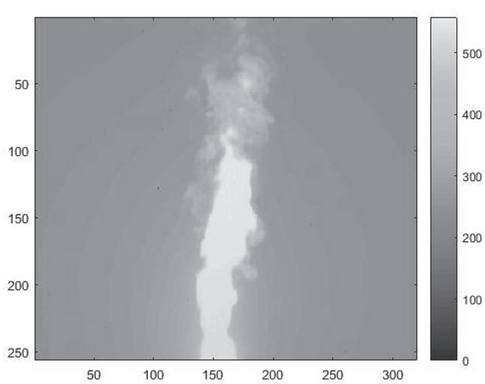
EXPERIMENTS AND DATA ACQUISITION

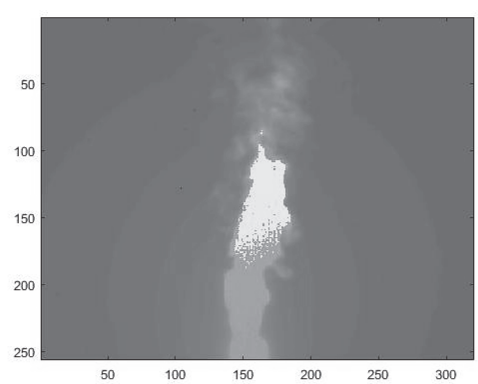
In the receipt time a large number of diagnostics methods have been employed to obtain information on the field of parameters. For analysis of relatively cold gaseous flows it is convenient to use Particle Image Velocimetry (PIV) method [5], however the application of this method is constrained by the temperature of the gas being studied. This is due to deformation and melting of introduced particles in high temperature flows [6]. As a result, PIV cannot be used in the studies of most types of flames and torches that exhibit high temperatures in the torch core.

To study pulsating combustion of gaseous fuel a thermographic camera was used. The experiment setup consisted of ejection burner positioned upright in a cube-shaped frame with the edge length of 500 mm. A duct made of silicon and having the internal diameter of 5 mm connected the burner to a pressure gas bottle. The duct was equipped with two valves. The upstream valve was responsible for setting constant pressure downstream it and, therefore the average flow rate of fuel fed to the burner. The second valve operated in on/off mode, creating pulsating fuel supply through periodic opening/closing at a preset frequency. The control signal was a meander with duty cycle of 0.5. The experiments were ran automatically and controlled through a computer-based graphical user interface.

These experiments employed the thermographic camera FLIR 7700M capable of sensing IF radiation with the wavelength in the range of 8 – 10 μm. Thermographic sequences were recorded in windowed mode with the resolution of 320 x 340 pixels to record sequences at the frequency of 412 Hz. Infrared radiation received by the camera allows computing the temperature field at the surface of the object under study given the known blackness of the object. Continuous oxidation of fuel takes place in the body of the burning torch, which makes the torch's content to be a mix of gases containing in the fuel, oxidizer (air in our case), underburned and completely burned combustion products. All these gases are of different structure (diatomic, triatomic, etc.) and, respectively, different blackness. This makes it hardly possible to reliably compute torch's blackness at each point. Moreover, due to the mass exchange and oxidation inside the torch's body this blackness continuously changes.

Nonetheless, when recording thermographic sequences at a preset and unchanged blackness, each thermograph represents the torch's radiation intensity field [7]. Since the radiation intensity of the torch core is greater, it will show through the combustion products located around it, so that the camera obtains the intensity field in the longitudinal section of the torch. Naturally, the temperature scale in this case is fictitious, however we will keep using Celsius degrees for determination of intensities or intensity ranges as numerical values obtained through thermographic camera processing of the signal received.





a **b**

Fig.1 (**a**) – Example of a thermograph obtained with the IF camera that observes a pulsing torch. The temperature scale is fictitious. (**b**) – Selected zone with the greatest radiation intensity ($T(i,j) > 543.5$).

The following procedure was used for this experiment. First, the burner was started and the steady mode set through adjustment of gas flow rate. Then the automatic on/off valve was initiated so that pulsations of gas supply were superimposed to the steady gas supply. The frequency of pulsations was 10 Hz. Then thermographic sequences were recorded for 10 seconds and, as a result, 4120 frames were obtained. The on/off valve pulsation frequency was then reduced to 9 Hz and the next sequence was recorded. These operations were repeated until the frequency was reduced to 2 Hz.

These experiments resulted in obtaining thermographic sequences radiation intensity fields in the longitudinal section of the torch at different pulsation rates.

RAW DATA PREPROCESSING

A total of 10 thermographic sequences were obtained: at the control action rates from 2 Hz to 10 Hz and with a continuously opened on-off valve (thereafter this mode is called 0 Hz action). Each thermographic sequence can be viewed as a two-dimensional matrix containing radiation intensity values $T(i,j)$, where i – row number, j – column number. The matrix size corresponds to the resolution of the thermographic camera (320 x 240 pixels) while the number of elements matches the number of pixels in each frame. This represents the overall thermographic sequence as a 3D array of values $T(i,j,k)$, where k is the frame number ($k = 1 \dots 4120$).

In order to preprocess the data we computed distributions of pixel quantities for certain temperatures in each frame. Most of each frame's area is taken by the background (Fig. 1), so for k-th frame we assume that the minimum temperature T_{min} is approximately equal to that for the background, which averaged to 245 degrees. The maximum temperature T_{max} is assumed to be equal to the greatest value of $T(i,j)$. The increment ΔT is found using the formula $\Delta T = (T_{max} - T_{min})/100$. For each T in the range from T_{min} to T_{max} with the increment of ΔT we shall find the number of pixels (elements) N_T with values $T - \frac{\Delta T}{2} < N_T \leq T + \frac{\Delta T}{2}$. By doing so we obtained the relationship $N_T(T)$ between the area (in pixels) with values within a certain temperature range and the average temperature from that range.

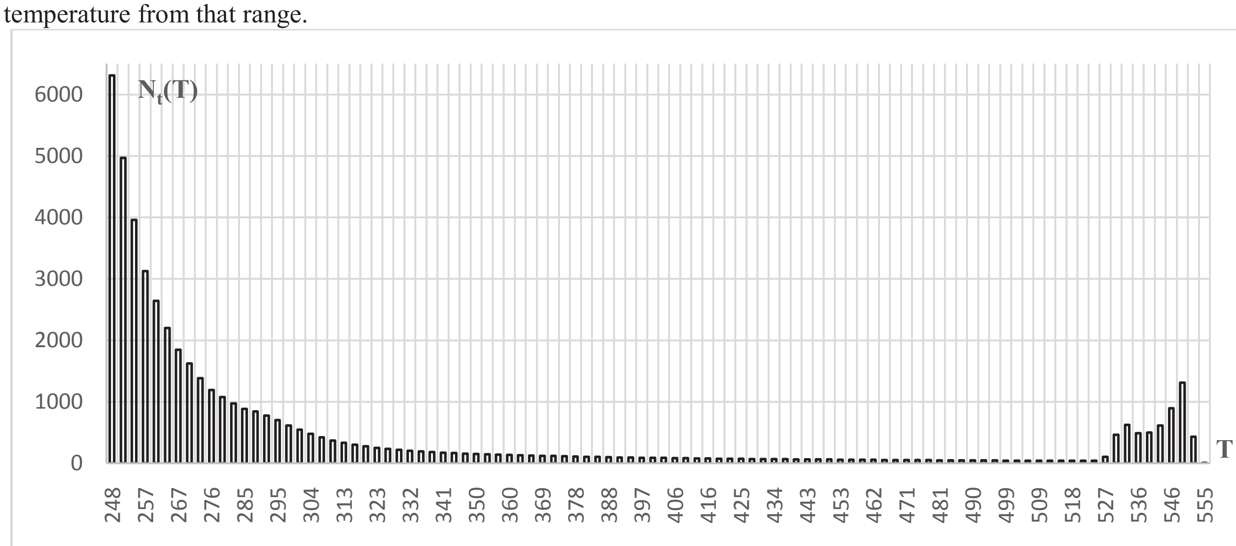


Fig. 2 Distribution $N_T(T)$ for k-th frame.

Analysis of this dependency and its comparison with the initial frame shows that the combustion zone, including the ignition initiation zone, is located in the temperature range of 525 – 555 degrees, while the torch core, i.e. the zone of the greatest radiation intensity, where the combustion process is fastest, is located in the range of 543.5 – 555 degrees.

Since the torch core parameters are among the primary factors that drive the results of combustion process, we focus on the impact of control action to the torch core. For each frame k of the sequence we shall find the number of pixels (elements) N_k with values $543.5 < N_k \leq 555$, so that we obtain the time chart $N_k(k)$ of changes of the torch core area in the lateral section.

FREQUENCY DOMAIN ANALYSIS

Frequency-domain analysis through Fast Fourier Transform (FFT) was run on each time-domain sequence. The outcome demonstrates that the first maximum of spectral density corresponds to the controlled pulsations rate. The spectrum also contains pronounced second and third harmonics.

It was shown that the torch core changes in size with the same frequency as the control action frequency even though it affected by numerous other factors, including the properties of the path between the on/off valve and the burner that also make their contribution in the oscillation.

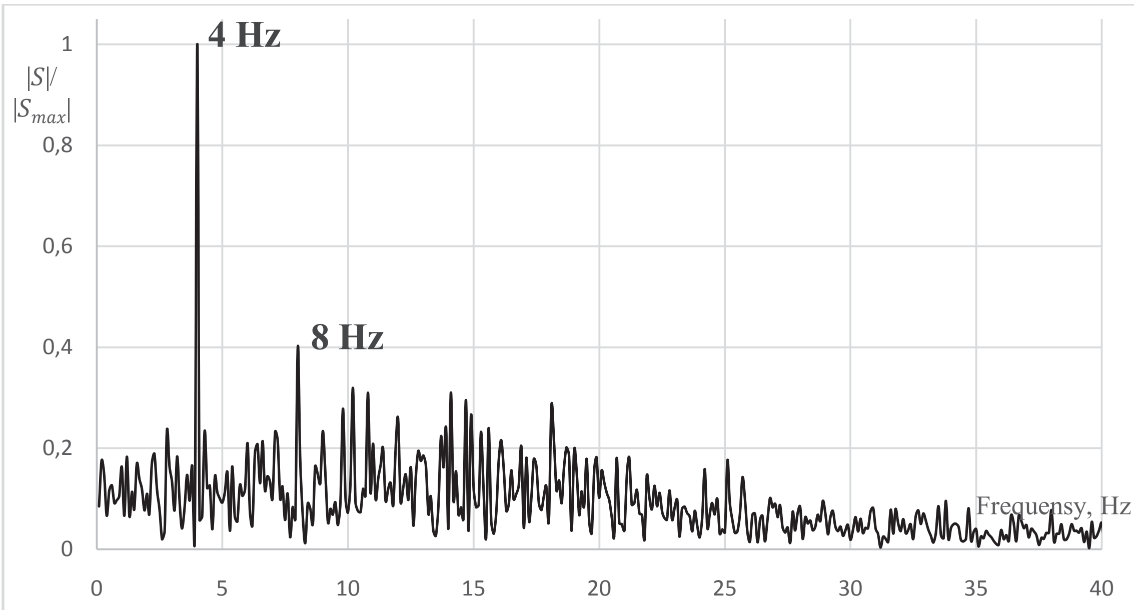


Fig. 3 Normalized spectrum of the time-domain series $N_k(k)$ at the control action rate of 4 Hz.

For each spectrum of the time-domain series signal-to-noise ratio (SNR) was calculated. Comparison of different SNR shows that maximum impact of pulsation control on torch radiation intensity takes place at the on/off valve opening rate of 4 Hz.

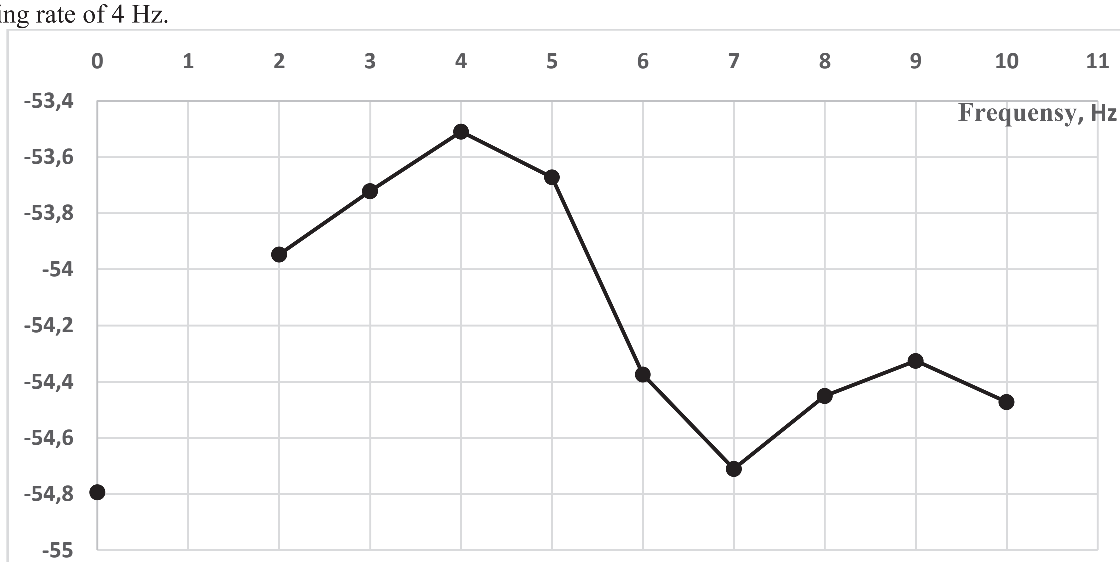


Fig. 4 Signal/noise ratio for each spectrum of the time-domain series. The 0 Hz point denotes the continuously open on/off valve regime (without pulsations).

We suggest that when SNR reaches its maximum (meaning that at that point the flame response to control action is most pronounced), the maximum reduction of NOx takes place. This is caused by the application of the pulsating mode. It should be noted that past experiments with gas analyzer demonstrate that minimum concentration of NOx in combustion products is reached on on/off valve action with frequency rate 4-5 Hz, that confirms our assumption.

SUMMARY

Time-domain series analyzed in this paper represent variation of selected area in lateral section that, in turn, means variation of volume of this area. Selected area is in the torch zone where the radiation intensity is greatest, i.e. where combustion rate is high and the most part of the fuel is burned in this area. Therefore, by changing combustion parameters in this particular area we can achieve the maximum effect of changes in the composition of combustion products and content of various components in them.

The advantage of data obtaining method used in our investigation is due the fact that the recording with an IF camera is free from any need for contact with the object under study, thus providing no impact on it. Although the thermal imaging are conventionally used to study solid surfaces, we applied this method to study gaseous torch. This offers a new approach and requires some additional clarifications to use it. Therefore, the paper provides an analysis of single thermograph and a description of the physical meaning of the obtained data in the thermal imaging discussed above. It worth mentioning that in most cases the design of power equipment makes it simple to install thermal imagers on combustion equipment (such as steam and water heating boilers, industrial furnaces, etc.).

The experimental data analysis shown above demonstrates that the signal obtained through remote recording of the torch with an IF camera carries certain information on the nature of the control action and can be used in feedback loops or other components of automatic systems that control pulsating combustion. We suggest that this method of torch diagnostics can be helpful for future studies and development of pulsating combustion control systems.

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